

FUEL EFFICIENT STRATEGIES FOR REDUCING CONTRAIL FORMATIONS IN UNITED STATES AIRSPACE

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Abstract

This paper describes a class of strategies for reducing persistent contrail formation in the United States airspace. The primary objective is to minimize potential contrail formation regions by altering the aircraft's cruising altitude in a fuel-efficient way. The results show that the contrail formations can be reduced significantly without extra fuel consumption and without adversely affecting congestion in the airspace. The contrail formations can be further reduced by using extra fuel. For the day tested, the maximal reduction strategy has a 53% contrail reduction rate. The most fuel-efficient strategy has an 8% reduction rate with 2.86% less fuel-burnt compared to the maximal reduction strategy. Using a cost function which penalizes extra fuel consumed while maximizing the amount of contrail reduction provides a flexible way to trade off between contrail reduction and fuel consumption. It can achieve a 35% contrail reduction rate with only 0.23% extra fuel consumption. The proposed fuel-efficient contrail reduction strategy provides a solution to reduce aviation-induced environmental impact on a daily basis.

Introduction

Aircraft-induced environmental impact has drawn more attention in recent years [1]. The three largest emission impacts include direct emission of greenhouse gases such as CO₂, emissions of NO_x, and persistent contrails. The emission of CO₂ and NO_x are related to fuel burn.

Contrails are clouds that are visible trails of water vapor made by the exhaust of aircraft engines. They appear and persist if the aircraft is flying in certain atmospheric conditions. Persistent contrails reduce incoming solar radiation and outgoing thermal radiation in a way that accumulates heat [2]. The global mean contrail cover in 1992 was estimated to double by 2015, and quadruple by 2050 due to the increase in air traffic [3]. Studies suggest that the environmental impact from persistent contrails is

estimated to be three to four times [4], or even ten times [5] larger than aviation-induced emissions. Therefore, concepts to reduce aircraft induced persistent contrail in a fuel efficient way needs to be explored to minimize the impact on the global environment.

Efforts have been made in the past years to reduce the persistent contrail formation. Gierens [6] and Noppel [7] reviewed various strategies for contrail avoidance. Mannstein [8] proposed a strategy to reduce the climate impact of contrails significantly by making small changes in individual flight altitude. Campbell [9] presented a methodology to optimally reroute aircraft trajectories to avoid the formation of persistent contrails with the use of mixed integer programming. Both methodologies require a flexible free flight and onboard contrail detection system. Fichter [10] showed that the global annual mean contrail coverage was reduced by downshifting the cruise altitude. Williams [11], [12] proposed strategies for contrail reduction by identifying fixed and varying maximum altitude restriction policy. These restrictions generally imply more fuel burn, and add congestion in the already crowded airspace at lower altitudes.

The objective of this paper is to develop strategies to reduce persistent contrail formation with consideration of fuel consumption and airspace congestion. Contrail frequency index is used to quantify the severity of contrail formation. The strategy for reducing persistent contrail formations is to minimize contrail frequency index by altering the aircraft's cruising altitude in a fuel-efficient way. A strategy using a cost function which penalizes extra fuel consumed while maximizing the amount of contrail reduction is proposed. It provides a flexible way to trade off between contrail reduction and fuel consumption. The analysis results show that the contrail frequency can be reduced to some extent without extra fuel consumption and without adding congestion to the airspace. The contrail frequency can be further reduced by using extra fuel.

The remainder of the paper is organized as follows. The Data and Model section provides the descriptions of atmospheric data, contrail model, aircraft data, and contrail frequency index. Next, contrail reduction strategies are described in the Contrail Reduction Strategies section. The results are demonstrated in Results section. Finally, a summary and conclusions are presented in Conclusions section.

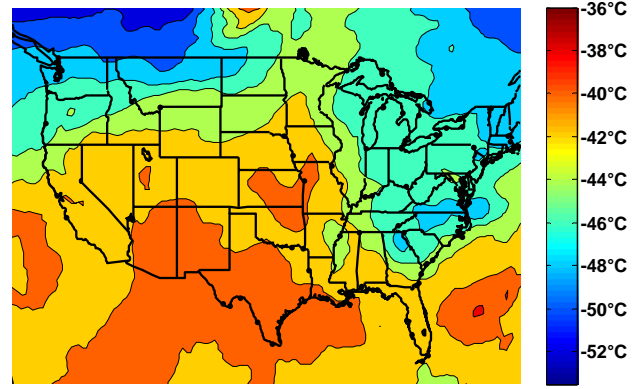
Data and Model

Atmospheric Data

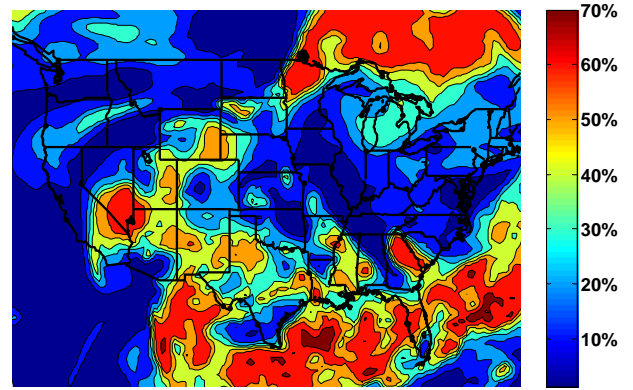
Contrails can be observed from surface data [13] and detected by satellite data [14]. Duda [15] has related the observations to numerical weather analysis output and showed that persistent contrail formation can be computed using atmospheric temperature and humidity data retrieved from the Rapid Updated Cycle (RUC) data provided by the National Oceanic and Atmospheric Administration (NOAA). Contrails can persist when ambient air is supersaturated with respect to ice, which means that relative humidity with respect to ice (RH_i) is greater than one hundred percent [16]. The RH_i can be computed from relative humidity with respect to water (RH_w) and temperature, which are available in the RUC data. The one-hour forecast and the 40-km RUC data are used in this paper. The data have temporal resolution of one hour, horizontal resolution of forty kilometer, and isobaric pressure level from 100 to 1000 hectopascal (hPa) in 25 hPa increment. The vertical range of interest in this study is from 150 hPa to 400 hPa, which is equivalent to pressure altitude of about 23,600 feet to 44,400 feet. The temperature and RH_w contours at 8AM eastern daylight time (EDT) on August 1, 2007 at pressure altitude 250 hPa, or 34,057 feet, are shown in Fig. 1a and 1b.

Contrail Model

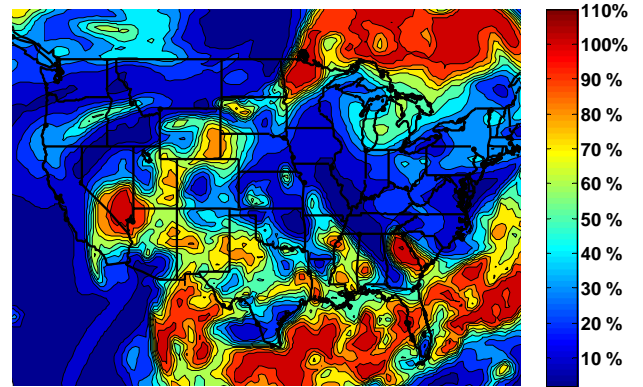
Contrails are clouds produced by aircraft at high altitude. The potential persistent contrail formation areas (contrail areas) are defined as areas with RH_i greater than or equal to 100%. RH_i can be computed from RH_w and temperature using the saturation vapor pressure coefficients of Alduchov [17], formulated as



(a) Temperature



(b) Relative humidity with respect to water



(c) Relative humidity with respect to ice

Figure 1. Contours of temperature, RH_w, and RH_i at 34,057 feet at 8AM EDT on August 1, 2007.

$$RH_i = RH_w \times \frac{6.0612e^{18.102T/(249.52+T)}}{6.1162e^{22.577T/(237.78+T)}}, \quad (1)$$

where T is the temperature in Celsius. The atmospheric profile shown in Fig. 1a and Fig. 1b can be translated to RHi, as shown in Fig. 1c.

The 40-km RUC data have (113×151) data points. The altitude level index l is defined as $l=1 \dots 11$ corresponding to isobaric pressure level at 400, 375, ..., 150 hPa. The altitude level, isobaric pressure level, and approximate corresponding flight level are listed in Table 1.

Table 1. Altitude level index, isobaric pressure level, and pressure altitude.

Level index	1	2	3	4	5	6
Pressure level (hPa)	400	375	350	325	300	275
Flight level (100 feet)	236	251	267	283	301	320
Level index	7	8	9	10	11	
Pressure level (hPa)	250	225	200	175	150	
Flight level (100 feet)	341	363	387	414	444	

The potential persistent contrail formation matrix (contrail matrix) at hour h at level l is defined as

$$\mathbf{R}_h^l = \begin{bmatrix} r_{1,1} & r_{1,2} & \cdots & r_{1,151} \\ \vdots & \vdots & \ddots & \vdots \\ r_{113,1} & r_{113,2} & \cdots & r_{113,151} \end{bmatrix}, \quad (2)$$

where $r_{i,j}$ is 1 if RHi $\geq 100\%$ at grid (i,j) , and 0 if RHi $< 100\%$.

Aircraft Data

The aircraft data used in this paper are extracted from the aircraft locations provided by the Federal Aviation Administration's (FAA's) Aircraft Situation Display to Industry (ASDI) data. The ASDI has a sampling rate of one minute. The same geometry grid used in the RUC data is used to generate the aircraft position matrix. The aircraft position matrix is defined as

$$\mathbf{A}_h^l = \begin{bmatrix} a_{1,1} & a_{1,2} & \cdots & a_{1,151} \\ \vdots & \vdots & \ddots & \vdots \\ a_{113,1} & a_{113,2} & \cdots & a_{113,151} \end{bmatrix}, \quad (3)$$

where $a_{i,j}$ is the number of aircraft within grid (i,j) flying closest to altitude level l at time t .

Contrail Frequency Index

Contrail frequency index is defined as the number of aircraft that would fly through potential contrail formation regions during a period of time. Center contrail frequency index is used to indicate the contrail severity in a given center [18]. To specify the location of the twenty U.S. centers in the grid scale, the center grid matrix is defined as

$$\mathbf{C}_{center} = \begin{bmatrix} c_{1,1} & c_{1,2} & \cdots & c_{1,151} \\ \vdots & \vdots & \ddots & \vdots \\ c_{113,1} & c_{113,2} & \cdots & c_{113,151} \end{bmatrix}, \quad (4)$$

where $c_{i,j}$ is one if the grid point is within the center and zero if not.

The center contrail frequency index is defined as the number of aircraft flying through contrail area at time t at level l , formulated as

$$CFI_{center,l,t} = \text{sum}(\mathbf{R}_t^l \circ \mathbf{A}_t^l \circ \mathbf{C}_{center}) = \sum_{i=1}^{113} \sum_{j=1}^{151} r_{i,j} a_{i,j} c_{i,j}, \quad (5)$$

where $\text{sum}(\bullet)$ is an operator that computes the sum of elements in a matrix, and \circ is the Hadamard product that performs the entrywise multiplication of two matrices. For strategic planning, the predicted contrail frequency index was used for contrail reduction strategies [18]. The predicted index is defined as

$$PCFI_{center,i,t} = \text{sum}(\hat{\mathbf{R}}_t^l \circ \hat{\mathbf{A}}_t^l \circ \mathbf{C}_{center}), \quad (6)$$

where $\hat{\mathbf{R}}_t^l$ is the contrail matrix computed from forecast weather and $\hat{\mathbf{A}}_t^l$ is computed from predicted aircraft locations.

Contrail Reduction Strategies

Contrail reduction strategies using contrail frequency index and fuel-efficient strategies are discussed in this section.

Use of contrail frequency index

Contrail frequency indices are used to quantify the severity of contrail formation. The strategy for reducing the persistent contrail formations is to minimize contrail frequency index by altering the aircraft's cruising altitude. Assume the aircraft at altitude level l at center k are made to fly a different level l' . The contrail frequency index changes to

$$CFI_{l,t}^{l'} = \text{sum}(\mathbf{R}_t^{l'} \circ \mathbf{A}_t^l \circ \mathbf{C}_{center}). \quad (7)$$

To solve the problem, with eleven altitude levels, a contrail frequency index matrix is formed as

$$\mathbf{CFI}_{center,t} = \begin{bmatrix} CFI_{1,t}^1 & CFI_{2,t}^1 & \cdots & CFI_{11,t}^1 \\ CFI_{1,t}^2 & CFI_{2,t}^2 & \cdots & CFI_{11,t}^2 \\ \vdots & \vdots & \ddots & \vdots \\ CFI_{1,t}^{11} & CFI_{2,t}^{11} & \cdots & CFI_{11,t}^{11} \end{bmatrix} \quad (8)$$

where the diagonal term $CFI_{l,t}^l$ is the contrail frequency index at level l before contrail reduction, and $CFI_{l,t}^{l'}$ is the contrail frequency index when guiding aircraft at level l to level l' . The contrail reduction is

$$\Delta CFI_{l,t}^{l'} = CFI_{l,t}^l - CFI_{l,t}^{l'}. \quad (9)$$

Note that when $l' > l$, not all aircraft have the ability to fly from level l to level l' . If altitude level l' is higher than an aircraft's maximal flight altitude, it stays at level l and is not counted in $CFI_{l,t}^{l'}$. In addition, if an aircraft crosses a sector boundary and causes sector overload, it stays at level l and does not add to $CFI_{l,t}^{l'}$.

The strategy is to find the smallest element in each column of $\mathbf{CFI}_{center,t}$. If the aircraft are limited to alter Δl levels, the solution is the smallest element in $[CFI_{l,t}^{l-\Delta l} \dots CFI_{l,t}^l \dots CFI_{l,t}^{l+\Delta l}]^T$ in each column. The solution is denoted as $[l'_1 \dots l'_{11}]$. Each l'_i means aircraft at flight level i is flying at level l'_i . If $l'_i = i$, the aircraft at level i did not alter. For example, $[1 \ 2 \ 3 \ 4 \ 4 \ 6 \ 8 \ 8 \ 9 \ 10 \ 11]$ means that the aircraft at level 5 is changing to level 4, and aircraft at level 7 is changing to 8.

As an example, the contrail frequency index matrix at Atlanta Center at 8AM EDT on August 1, 2007 is

0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0	1	0	0	0	0	2	0	0	1	0
28	26	31	33	10	52	68	105	51	6	7
57	74	43	25	13	76	104	148	71	5	10
69	29	44	33	28	105	128	209	132	9	14
16	12	5	8	5	62	47	36	22	6	0
0	2	0	0	5	65	45	35	19	6	0
0	0	0	0	4	71	108	36	19	6	0
0	0	0	0	10	74	122	33	19	0	0

The diagonal elements of the matrix are shown in bold for clarity. If the aircraft are only allowed to move one level up or down ($\Delta l=1$) the matrix becomes

0	0	x	x	x	x	x	x	x	x	x
0	0	0	x	x	x	x	x	x	x	x
x	0	0	0	x	x	x	x	x	x	x
x	x	0	0	0	x	x	x	x	x	x
x	x	x	33	10	52	x	x	x	x	x
x	x	x	x	13	76	104	x	x	x	x
x	x	x	x	x	105	128	209	x	x	x
x	x	x	x	x	x	47	36	22	x	x
x	x	x	x	x	x	x	35	19	6	x
x	x	x	x	x	x	x	x	19	6	0
x	x	x	x	x	x	x	x	x	0	0

where \times indicates an invalid move. The sum of the diagonals, 275, is the center contrail frequency index before reduction. For flight level 7, flying the aircraft one level higher would reduce the contrail frequency from 128 to 47. Similarly, guiding aircraft from level 5 to 4, 6 to 5, 8 to 9, and 10 to 11 would reduce contrail frequency. The solution for this example can be denoted as $[1 \ 2 \ 3 \ 4 \ 4 \ 5 \ 8 \ 9 \ 9 \ 11 \ 11]$. The center contrail frequency index after reduction is 153, a 44% reduction. The simulation results are shown in Fig. 2. The color lines indicate the contrail regions at different altitudes. The color dots indicate the aircraft flying through the contrail areas. Different colors

indicate different altitudes, from blue at flight level 236, to red at 444. There are 275 dots in Fig. 2a, which is the center contrail frequency at all flight levels. When the reduction strategy is applied, the aircraft flying at flight level 341 (level 7, light green dots) were flying at one level up. The move eliminated all the light green (level 7) in Fig. 2a and only a few yellow dots (level 8) were added in Fig. 2b. Also, notice that the red dots (level 10) are eliminated and the number of light blue dots is reduced. The total dots in Fig. 2b are 153.

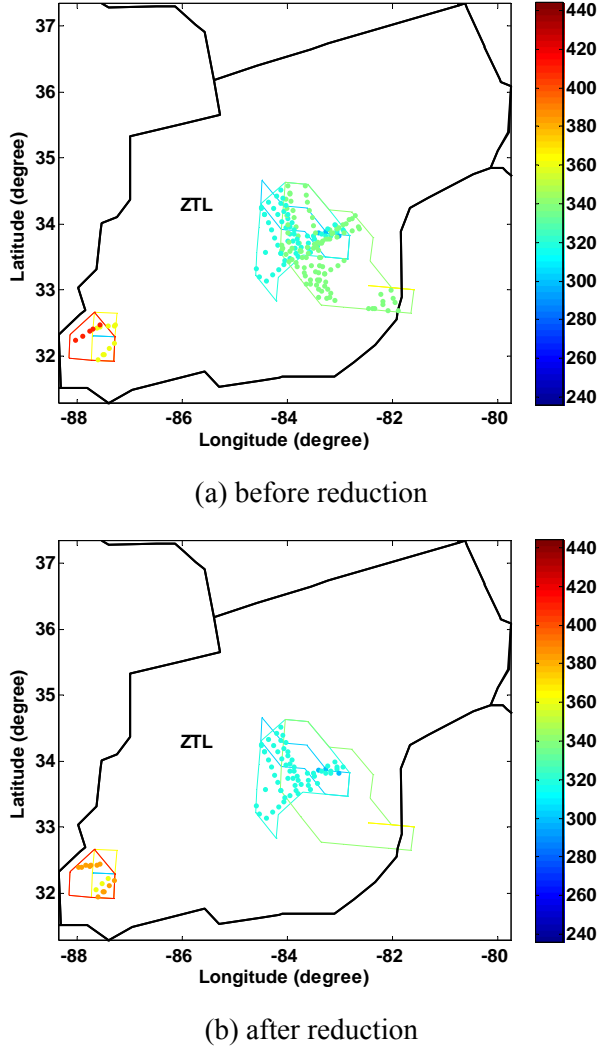


Figure 2. Contrail formation area before and after reduction strategy at Atlanta Center at 8AM (EDT) on August 1, 2007.

Note that if the aircraft are allowed to move two levels up or down ($\Delta l = 2$), the contrail frequency can be further reduced to 99, a 64% reduction. The more

levels the aircraft are allowed to move up or down, the more contrail reduction can be achieved.

Fuel efficient strategies

Altering cruising altitude changes the aircraft fuel consumption. In order to inspect the environmental impact of contrail reduction strategies, fuel consumption is considered in the strategies. The fuel consumption model used in this analysis is based on the System for assessing Aviation's Global Emissions (SAGE) developed by the FAA [19]. In general, aircraft consume less fuel when cruising at higher altitudes.

The fuel burn matrix is defined as

$$\mathbf{FB}_{center,t} = \begin{bmatrix} FB_{1,t}^1 & FB_{2,t}^1 & \cdots & FB_{11,t}^1 \\ FB_{1,t}^2 & FB_{2,t}^2 & \cdots & FB_{11,t}^2 \\ \vdots & \vdots & \ddots & \vdots \\ FB_{1,t}^{11} & FB_{2,t}^{11} & \cdots & FB_{11,t}^{11} \end{bmatrix}, \quad (10)$$

where the diagonal term $FB_{l,t}^l$ is the fuel-burnt for all aircraft at level l at a given center at time t before contrail reduction, and $FB_{l,t}^{l'}$ is the total fuel-burnt when guiding aircraft at level l to level l' . When aircraft are guided from level l to l' , the extra fuel-burnt is

$$\Delta FB_{l,t}^{l'} = FB_{l,t}^{l'} - FB_{l,t}^l. \quad (11)$$

$\Delta FB_{l,t}^{l'} < 0$ implies fuel saving instead of consuming extra fuel. The objective is to achieve a large reduction in contrail frequency index ($\Delta CFI_{l,t}^{l'}$) with little increase in fuel consumption ($\Delta FB_{l,t}^{l'}$). In other words, the best move is in the altitude direction with the steepest CFI reduction for unit of extra-fuel consumed.

Consider the same example in the previous subsection. There are four cruising altitude changes. Changing from level 7 to 8, 8 to 9, and 10 to 11 reduces contrail frequency by 88. These changes reduce fuel-burnt by 1,857 kg. On the other hand, changing from level 5 to 4 and 6 to 5 reduces contrail frequency by 34 with 1,914 kg of extra fuel. Although the actual environmental cost of contrail frequency is still unknown, it seems unworthy to

consume 1,914 kg of fuel to reduce contrail frequency by 34. The first strategy requires 21 kg of fuel to reduce a unit of CFI compared to 56 kg for the second strategy.

Assume the aircraft can move up or down two levels. The **CFI** matrix is

0	0	0	×	×	×	×	×	×	×	×	×
0	0	0	0	×	×	×	×	×	×	×	×
0	0	0	0	0	×	×	×	×	×	×	×
×	1	0	0	0	0	×	×	×	×	×	×
×	×	31	33	10	52	68	×	×	×	×	×
×	×	×	25	13	76	104	148	×	×	×	×
×	×	×	×	28	105	128	209	132	×	×	×
×	×	×	×	×	62	47	36	22	6	×	×
×	×	×	×	×	×	45	35	19	6	0	×
×	×	×	×	×	×	×	36	19	6	0	×
×	×	×	×	×	×	×	×	19	0	0	×

In this case, the most contrail reduction solution is [1 2 3 4 4 4 9 9 9 11 11], resulting in a contrail reduction of 176 (64%) and fuel-burnt increased by 1,025 kg. This results in a fuel consumption gradient of 5.8 kg/CFI. The most fuel-efficient solution is [1 2 3 4 5 8 9 9 9 11 11], with the contrail reduction of 104 (38%) and fuel-burnt reduced by 2,338 kg. This most fuel-efficient strategy achieved less contrail reduction with the benefit of less fuel consumed.

In some cases, the most fuel-efficient strategy does not provide enough contrail reduction. The fuel-

efficient contrail reduction strategy using a cost function starts from the most fuel-efficient model and trades off small amount of extra fuel-burnt for large contrail reduction. The strategy would move aircraft only if the contrail reduction benefit exceeds the fuel-burnt cost. The aircraft would be guided from level l to l' only if

$$\Delta CFI_{l,t}'' > \frac{\alpha}{1000} \Delta FB_{l,t}'', \quad (12)$$

where $\Delta CFI_{l,t}''$ and $\Delta FB_{l,t}''$ are defined in Eq. (9) and Eq. (11) and α is the contrail reduction cost for every 1,000 kg fuel consumed. The fuel-efficient strategy achieves more contrail reduction for the cost of extra fuel consumption. The value of α has to be determined based on further understandings of the relative environmental impacts of CO₂ and contrails. α is used in this analysis as a variable to generate different combinations of extra fuel consumption and reduction in contrails.

Results

Twenty continental U.S. enroute center contrail frequencies on August 1, 2007 were used to evaluate the contrail reducing strategy. The center contrail frequency before and after various contrail reducing strategies in twenty U.S. enroute centers at 8AM EDT is shown in Fig. 3.

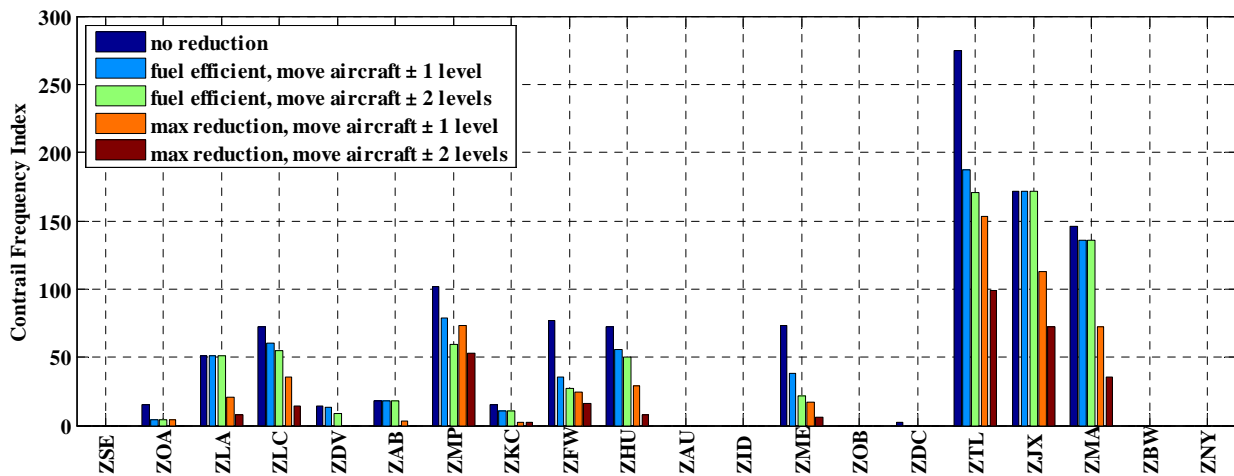


Figure 3. Center contrail frequency index before and after contrail reduction strategies at 8AM EDT on August 1, 2007.

The strategies vary from achieving maximal contrail reduction to most fuel-efficient strategy with aircraft allowed to move one or two levels up or down. In general, allowing aircraft to move two levels provides more reduction than allowing one; maximal contrail reduction strategies provide more reduction than fuel-efficient strategies at the price of more fuel consumption. Note that fuel-efficient strategies provide no reduction at Jacksonville Center (ZJX) and Los Angeles Center (ZLA). This is because the potential contrail regions are located at the top of the centers making it impossible to fly over the regions to reduce contrail formations and save fuel. The result for the entire U.S. is summarized in Table 2. When allowing aircraft to move two levels, the maximal contrail reduction strategy reduces contrail frequency by 472 (43%) more compared to the most fuel-efficient strategy while using 29,237 kg (1.11%) more fuel.

Table 2. Results of contrail reduction strategies over U.S. at 8AM EDT on August 1, 2007.

Contrail reduction strategy	Contrail reduced	Extra fuel-burnt
Max reduction $\Delta l=1$	558(51%)	5,214 kg (0.2%)
Fuel-efficient $\Delta l=1$	244(23%)	-11,134 kg (-0.42%)
Max reduction $\Delta l=2$	791(72%)	10,663 kg (0.41%)
Fuel-efficient $\Delta l=2$	319(29%)	-18574 kg (-0.71%)

The results of contrail reduction analysis over twenty-four-hour period on August 1, 2007 are shown in Fig. 4. The strategies allow aircraft to move two levels up or down and include the maximal contrail reduction, the most fuel-efficient, and fuel-efficient strategies with contrail cost. It shows that more contrail reduction can be achieved by burning extra fuel. The results for the whole day are summarized in Table 3. On this day, the maximal reduction strategy has a 53% contrail reduction rate. The most fuel-efficient strategy has only a 8% reduction rate with 2.86% less fuel-burnt compared to maximal reduction strategy. A higher value of α lowers the amount of contrail reduction and uses less fuel. For $\alpha=40$, the contrail reduction is 35% with only 0.23% extra fuel consumption. Figure 5 shows the contrail reduction versus extra fuel consumption for various α values. This fuel-efficient strategy with

contrail cost provides a flexible way to trade off between contrail reduction and fuel consumption.

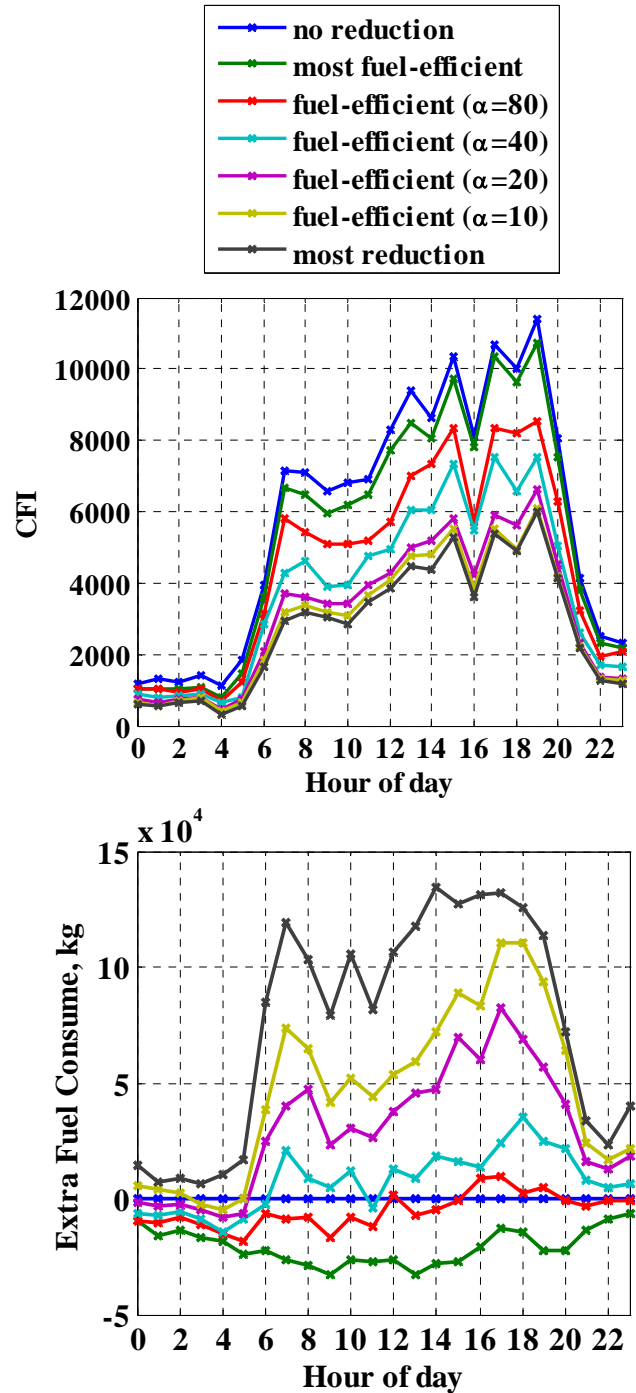


Figure 4. Contrail reduction and extra fuel-burnt using different strategies on August 1, 2007.

Table 3. Results of contrail reduction strategies over U.S. on August 1, 2007.

Contrail reduction strategy	Contrail reduced	Extra fuel-burnt
Max reduction	73,352(53%)	1,794,924 kg (2.24%)
Fuel-efficient $\alpha=10$	69,794(50%)	1,117,341 kg (1.39%)
Fuel-efficient $\alpha=20$	63,901(46%)	720,908 kg (0.9%)
Fuel-efficient $\alpha=40$	48,688(35%)	182,567 kg (0.23%)
Fuel-efficient $\alpha=80$	31,971(23%)	-122,375 kg (-0.15%)
Most fuel-efficient	10,260(8%)	-496,211 kg (-0.62%)

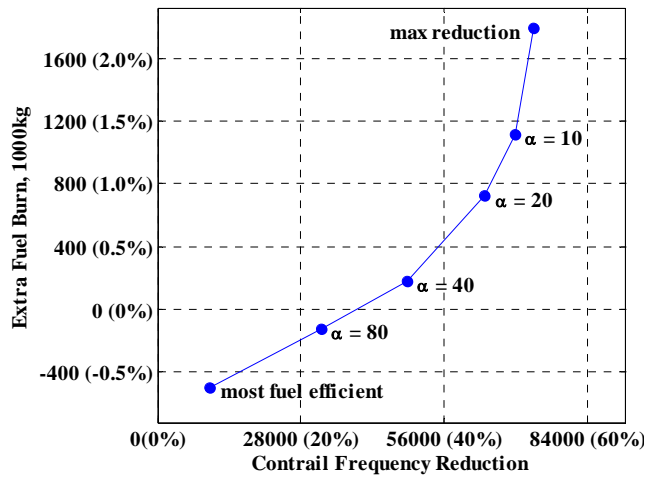


Figure 5. Contrail reduction versus extra fuel-burnt on August 1, 2007.

Conclusions

The paper develops a class of strategies for reducing the persistent contrail frequency with minimal impact on extra fuel consumed and airspace congestion. The strategy of reducing the persistent contrail formations is to minimize the contrail frequency index by altering the aircraft's cruising altitude in a fuel-efficient way without adding to airspace congestion. The results show that the contrail frequency can be reduced by a significant amount without extra fuel consumption. The contrail frequency can be further reduced by using extra fuel. For the day tested, the maximal reduction strategy has a 53% contrail reduction rate. The most fuel-efficient strategy has an 8% reduction rate with 2.86% less fuel-burnt compared to maximal reduction strategy. Using a cost function which penalizes extra fuel consumed while maximizing the amount of

contrail reduction provides a flexible way to trade off between contrail reduction and fuel consumption. It has a 35% contrail reduction rate with only 0.23% extra fuel consumption. The proposed fuel-efficient contrail reduction strategy provides a planning solution to reduce aviation-induced environmental impact on a daily basis.

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